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EFFECT OF SALTATING SEDIMENT ON FLOW RESISTANCE AND BED ROUGHNESS IN OVERLAND FLOW

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ABSTRACT

The acceleration of saltating grains by overland flow causes momentum to be transferred from the flow to the grains, thereby increasing flow resistance and bed roughness. To assess the impact of saltating sediment on overland flow hydraulics, velocity profiles in transitional and turbulent flows on a fixed sand-covered bed were measured using hot-film anemometry. Five discharges were studied. At each discharge, three flows were measured: one free of sediment, one with a relatively low sediment load, and one with a relatively high sediment load. In these flows from 83 to 90 per cent of the sediment was travelling by saltation. As a result, in the sediment-laden flows the near-bed velocities were smaller and the velocity profiles steeper than those in the equivalent sediment-free flows. Sediment loads ranged up to 87·0 per cent of transport capacity and accounted for as much as 20·8 per cent of flow resistance (measured by the friction factor) and 89·7 per cent of bed roughness (measured by the ratio of the roughness length to median grain diameter). It is concluded that saltating sediment has a considerable impact on overland flow hydraulics, at least on fixed granular beds. Saltation is likely to have a relatively smaller effect on overland flow on natural hillslopes and agricultural fields where form and wave resistance dominate. Still, saltation is generally of greater significance in overland flow than in river flow, and for this reason its effect on overland flow hydraulics is deserving of further study. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: overland flow; flow resistance; bed roughness; saltation; hillslopes

INTRODUCTION

Resistance to overland flow has traditionally been partitioned into several categories (e.g. Abrahams and Parsons, 1994). Grain resistance is imparted by soil grains and microaggregates and is the result of shear and pressure forces acting on the grains and aggregates. Form resistance is caused by stones, litter, vegetation and microtopographic protuberances that obstruct the flow and give rise to pressure differences between the upflow and downflow sides of the obstacles. Wave resistance includes free surface disturbances and spill resistance. The former refer to the energy dissipated in maintaining an uneven water surface, while the latter occurs when abruptly diverging streamlines result in a sudden forced reduction in velocity. Finally, rain resistance is due to velocity retardation as flow momentum is transferred to accelerate the raindrop mass to the flow velocity. No mention has hitherto been made in the overland flow literature of another kind of resistance, herein termed transport resistance. Transport resistance is due to the acceleration of saltating grains by the flow. Acceleration of the grains involves the transfer of momentum from the flow to the grains and results in a decrease in flow velocity. This process has been well studied in aeolian transport (e.g. Bagnold, 1941; Anderson and Haff, 1991; McEwan, 1993; McKenna Neuman and Nickling, 1994), where laboratory measurements have shown that saltating sand causes velocities near the bed to decrease and the velocity profile to steepen (i.e. du/dz increases, where u is the time-averaged point velocity at distance z above the bed). Modification of the velocity profile is believed to be a fundamental control of the self-regulating saltation process in both air and water (e.g. Owen, 1964; Bagnold, 1973; Smith and McLean, 1977; Grant and Madsen, 1982; Ungar and Haff, 1987; Anderson *et al*., 1991).

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Two recent flume studies have suggested that saltation may also have an important effect on flow resistance in overland flow. Abrahams and Atkinson (1993) investigated the relation between grain velocity and sediment concentration in overland flow. As part of the study, they regressed mean flow velocity against water discharge and sediment concentration. Water discharge entered the regression equation first and accounted for 93·1 per cent of the total variance. Sediment concentration then entered, adding 4·0 per cent to the explained variance. The regression coefficient associated with concentration had a negative sign, indicating that mean velocity decreased as sediment concentration and, hence, sediment load increased. The most plausible explanation for this finding is that as sediment load increased, greater momentum was extracted from the flow by the saltation process, thereby reducing flow velocity.

In the second study, Li and Abrahams (1997) examined the controls of the ratio of the mean flow velocity to the leading edge velocity of a salt plume. The leading edge velocity is widely assumed to be equivalent to the surface velocity. In transitional and turbulent flow the ratio was found to vary directly with Reynolds number and inversely with sediment load. In all experiments the sediment was travelling in saltation. Using hot-film anemometry, the authors measured the velocity profiles of the same flow free of sediment and with a low sediment load and a high sediment load. The velocity profiles shifted to the left and became steeper as sediment load increased. Again, the most plausible explanation is that greater momentum was extracted from the flow as sediment load increased, causing the mean flow velocity to decrease and the velocity profile to steepen.

When a velocity profile shifts to the left and/or becomes steeper, there are corresponding changes in resistance to flow and bed roughness. In this paper, resistance to flow is measured by the Darcy–Weisbach friction factor:

$$f = 8gsh/U^2 \tag{1}$$

where g is the acceleration of gravity, h is the mean flow depth, s is the energy slope and U is the mean flow velocity. Bed roughness, on the other hand, is represented by the dimensionless ratio z_o/D, where z_o is the bed roughness length and D is the median size of the bed sediments. The bed roughness length is defined by the velocity profile:

$$u = m \ln(z/z_o) \tag{2}$$

where m is the slope of the profile and z_o is the zero-velocity intercept or the value of z when $u = 0$. It seems clear that saltating sediment in overland flow causes both f and z_o/D to increase, but there are no data available on the magnitude of the increases in these quantities. The purpose of this study, therefore, was to assess the impact of saltating sediment on flow resistance and bed roughness in the simple case of overland flow in a flume with a fixed bed coated with sand. Because flow resistance and bed roughness derive solely from the grains on the bed and the saltating sediment, the problem of isolating the effect of saltating sediment becomes tractable.

SET-UP AND METHODS

The flume was 5·2 m long and 0·40 m wide with a smooth aluminium floor and plexiglas walls (Figure 1). It consisted of two parts. The lower part was 3·6 m long and inclined at 2·7°, while the upper part was 1·6 m long and inclined at 8·3°. A well sorted silica testing sand (ASTM C-190) with a median diameter D of 0·00074 m was glued to the floor of the lower part of the flume. Water entered the flume by overflowing from a head tank. Five discharges were employed in the experiments (Table I). For these discharges the Reynolds number defined by $Re = 4hU/v$, where v is the kinematic viscosity of the water, ranged from 6463 to 13 679 (Table I), indicating that the flows were either transitional or turbulent. At each discharge, three flows were measured: one free of sediment, one with a relatively low sediment load, and one with a relatively high sediment load (Table I). The sediment, which was the same size as that glued to the bed, was supplied from a hopper positioned above the upper end of the lower part of the flume. The sediment load q_s was determined by collecting volumetric samples of the water–sediment mixture at the flume outlet. According to Hu and Hui's (1996) equations, during the experiments 83 to 90 per cent of the sediment was transported in saltation (Table I). Rolling is considered an incipient form of, and is therefore included in, saltation (Bagnold, 1973).

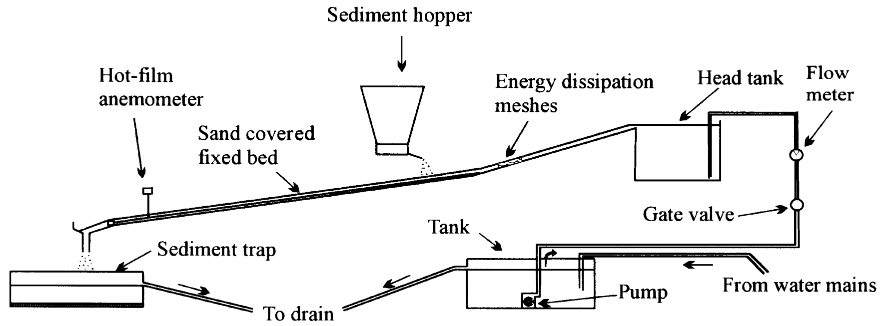

Figure 1. Sketch of the flume

Table I. Experimental data

Flow*	Unit discharge ($m^2 s^{-1}$)	*Re*	Percentage in saltation† (%)	q_s ($kg s^{-3}$)	C ($kg m^{-3}$)	T_w ($kg s^{-3}$)	$\%q_s$ (%)	h (m)	h_s (m)	m	c	U ($m s^{-1}$)	f	f_t	$\%f_t$ (%)	z_o (m)	z_{ot} (m)	$\%z_{ot}$ (%)
1F	0·00160	6464	0	0	0	0·433	0	0·00450	0·0043	0·1204	1·1946	0·390	0·109	0	0	0·0000491	0	0
1L	0·00160	6463	90·26	0·0678	6·94	0·430	15·78	0·00455		0·1270	1·2328	0·387	0·112	0·0031	2·66	0·0000609	0·0000118	19·33
1H	0·00160	6300	90·09	0·2645	27·06	0·404	65·47	0·00460		0·1856	1·5734	0·373	0·122	0·0132	10·82	0·0002081	0·0001590	76·41
2F	0·00205	7918	0	0	0	0·542	0	0·00500	0·0049	0·0999	1·0778	0·430	0·100	0	0	0·0000206	0	0
2L	0·00205	8031	88·44	0·0766	6·12	0·542	14·14	0·00510		0·1225	1·2192	0·427	0·103	0·0034	3·29	0·0000476	0·0000270	56·66
2H	0·00205	7466	88·13	0·4062	32·45	0·467	86·99	0·00520		0·1678	1·4294	0·390	0·126	0·0262	20·76	0·0001997	0·0001791	89·67
3F	0·00255	9528	0	0	0	0·668	0	0·00550	0·0055	0·1329	1·2997	0·470	0·092	0	0	0·0000566	0	0
3L	0·00255	9646	86·95	0·0687	4·42	0·669	10·26	0·00560		0·1498	1·4056	0·468	0·094	0·0024	2·54	0·0000841	0·0000275	32·72
3H	0·00255	9325	86·67	0·5129	32·98	0·616	83·21	0·00570		0·1779	1·5332	0·444	0·106	0·0146	13·75	0·0001807	0·0001241	68·69
4F	0·00319	11672	0	0	0	0·806	0	0·00630	0·0062	0·1315	1·2963	0·503	0·092	0	0	0·0000523	0	0
4L	0·00319	11983	84·70	0·1874	9·63	0·821	22·83	0·00645		0·1408	1·3643	0·505	0·093	0·0016	1·67	0·0000619	0·0000096	15·48
4H	0·00319	11668	84·33	0·5704	29·30	0·763	74·74	0·00660		0·1733	1·5175	0·481	0·105	0·0135	12·77	0·0001574	0·0001051	66·76
5F	0·00364	13672	0	0	0	0·990	0	0·00670	0·0066	0·1231	1·3055	0·555	0·080	0	0	0·0000248	0	0
5L	0·00364	13679	83·74	0·1539	6·92	0·965	15·95	0·00680		0·1432	1·4112	0·544	0·085	0·0053	6·22	0·0000525	0·0000277	52·78
5H	0·00364	13177	83·40	0·7491	33·68	0·879	85·23	0·00700		0·1913	1·6392	0·512	0·098	0·0183	18·55	0·0001900	0·0001651	86·95

*F, sediment free; L, low sediment load; H, high sediment load
† includes rolling

The velocity profile of each flow was measured using a TSI model 1231W hot-film anemometer located on the centreline of the flume 0·5 m from its lower end. Hot-film anemometers are notoriously fragile, and model 1231W is no exception. However, this model is purportedly the most rugged probe manufactured by TSI (TSI technical advisor, personal communication, 1996). Hot-film anemometers are also sensitive to the temperature of the ambient fluid (Bruun, 1995, p. 114, 219). Although an effort was made to hold water temperature constant, it varied between 17·6 and 17·8°C during the course of the experiments. The effect of this variation was eliminated by correcting the probe readings to a standard temperature using a pre-established calibration curve. Finally, hot-film anemometers are susceptible to signal noise caused by air bubbles at the probe tip (Bruun, 1995, p. 114). No problems of this sort were encountered in the present experiments, as the turbulent flow carried away bubbles as soon as they formed.

The voltage signal from the anemometer was recorded at 100 Hz over 20 s and sent to a data acquisition system. This system averaged and calibrated the signal to give the time-averaged point velocity u. Two measurements were made at each point, and there were five to seven points in each profile. The mean bed level was estimated to be about 0·5D below the tops of the sand grains. The height of the sensor tip above the bed z was determined by a vernier scale which could be read to an accuracy of 0·1 mm. The flow depth h was read from the same scale when the probe tip was at the water surface. As a check on the accuracy of this methodology, the measured depths of the sediment-free flows were compared with the depths h_s predicted by the Savat (1980) algorithm. This algorithm has been extensively tested by Govers and Rauws (1986), Rauws (1988) and Everaert (1991) and has been shown to give good unbiased estimates of flow depths in shallow,

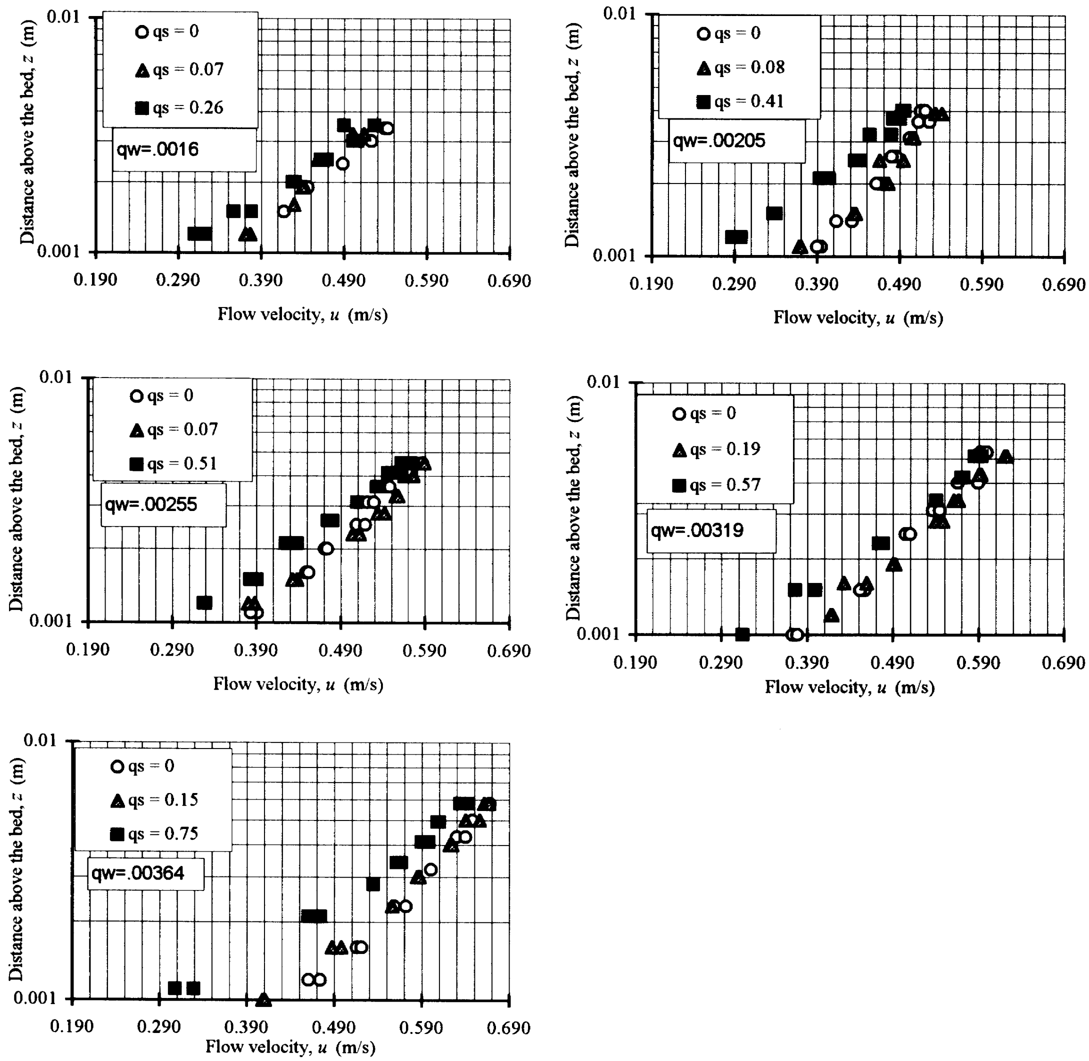

Figure 2. Velocity profiles for each discharge q_w ($m^2 s^{-1}$) and sediment load q_s ($kg s^{-1}$)

sediment-free overland flow on fixed granular beds. The measured and predicted flow depths are reported in Table I and never differ by more than 0·2 mm or 4·4 per cent.

ANALYSIS

Velocity profiles

The velocity profiles all appear linear on semilogarithmic graph paper (Figure 2) and have correlation coefficients exceeding 0·95. Each velocity profile was therefore fitted by an equation of the form:

$$u = m \ln z + c \tag{3}$$

by regressing u against $\ln z$ (Bergeron and Abrahams, 1992). The values of the regression coefficients m and c are listed in Table I. Equation 3 may also be written in the form:

$$u = m \ln z - m \ln z_o \tag{4}$$

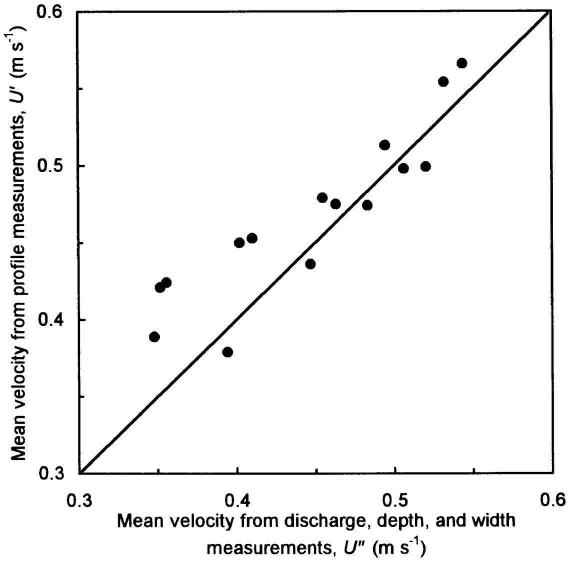

Figure 3. Graph of mean velocity from profile measurements against mean velocity from discharge, depth and width measurements

where

$$z_o = \exp(-c/m) \tag{5}$$

The values of z_o were computed using Equation 5 and are recorded in Table I.

Mean flow velocity

Given the present experimental design, it was possible to obtain two independent estimates of U. The first, denoted by U', was calculated from:

$$U' = m\left(\ln\frac{h}{z_o} - 1\right) + m\left(\frac{z_o}{h}\right) \tag{6}$$

which was obtained by integrating Equation 2 between z_o and h and dividing by h. The second, denoted by U'', was computed by dividing the discharge by the product of the flow width and depth. Figure 3 shows that, while there is some scatter, the agreement between U' and U'' is quite good. Consequently, U' and U'' were averaged to obtain U for each flow (Table I).

Transport resistance

Knowing U, f was computed for each flow using Equation 1 (Table I). For each flow the grain resistance f_g is equal to f for the sediment-free flow of the same discharge, while transport resistance f_t is equal to $f - f_g$ (Table I). Logically, f_t is directly related to the sediment concentration C. This is confirmed by non-linear regression which yields the equation:

$$f_t = 0{\cdot}00025C^{1{\cdot}23} \tag{7}$$

with $R^2 = 0{\cdot}94$ and $N = 15$ (Figure 4).

The percentage of total resistance due to transport resistance is given by $\%f_t = 100f_t/f$ (where f relates to the sediment-laden flow). Table I reveals that $\%f_t$ ranges up to 20·8 per cent. Given that q_s is below transport capacity T_w in the present experiments, the observed variation in $\%f_t$ raises two questions. (1) Is the variation in $\%f_t$ related to the ratio of q_s *to* T_w? (2) If so, how much larger is $\%f_t$ likely to become when $q_s = T_w$? To answer

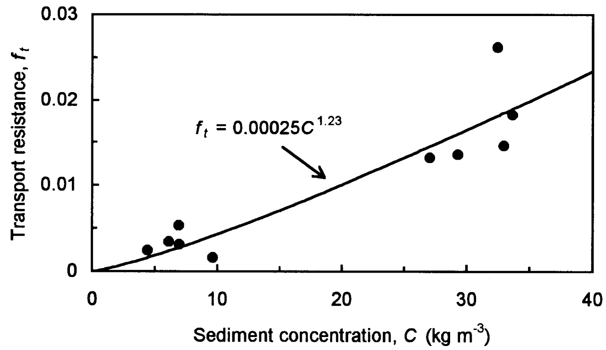

Figure 4. Graph of transport resistance against sediment concentration

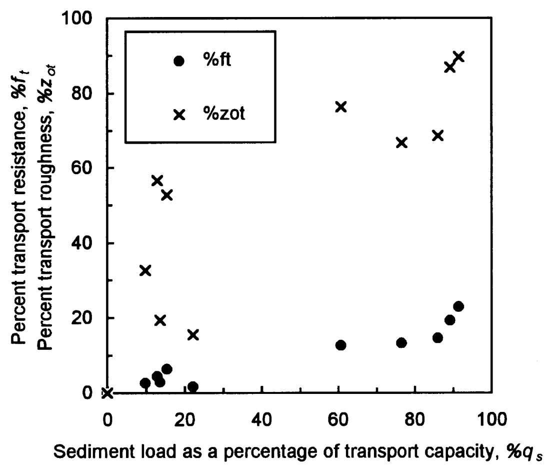

Figure 5. Graph of percentage of transport resistance and percentage of transport roughness against sediment load as a percentage of transport capacity

these questions, T_w was estimated for each experiment (Table I) using Abrahams *et al.*'s (1998) equation for 0·00074-m sand:

$$\log T_w = -3{\cdot}038 + 1{\cdot}726 \log(\omega - \omega_c) - 1{\cdot}212 \log h \tag{8}$$

where $\omega = \rho ghsU$ is flow power, ρ is the fluid density, and ω_c is the critical value of ω. The quantity $\%q_s = 100q_s/T_w$ was then computed and graphed against $\%f_t$. Figure 5 shows a strong relationship between $\%f_t$ and $\%q_s$ and suggests that for the flows investigated here even at transport capacity $\%f_t$ probably never exceeds 30 per cent.

Transport roughness

That part of the bed roughness z_o/D attributable to saltating sediment is herein termed the transport roughness and is denoted by z_{ot}/D. For each sediment-laden flow in the present experiments, z_{ot} is equal to z_o for the flow minus z_o for the corresponding sediment-free flow (Table I). Logically z_{ot}/D is related to C, and this is confirmed by non-linear regression which yields the equation:

$$z_{ot}/D = 0{\cdot}0026\, C^{1{\cdot}26} \tag{9}$$

with $R^2 = 0{\cdot}96$ and $N = 15$ (Figure 6).

The percentage of total bed roughness due to saltating sediment is indicated by $\%z_{ot} = 100z_{ot}/z_o$ (where z_o relates to the sediment-laden flow). Table I reveals that $\%z_{ot}$ increases with $\%q_s$ and reaches 89·7 per cent with $\%q_s = 87{\cdot}0$ per cent. Thus, $\%z_{ot}$ increases with $\%q_s$ much more rapidly than does $\%f_t$ (Figure 5). The difference between the rates of increase of $\%f_t$ and $\%z_{ot}$ can be explained with the aid of simplified expressions for $\%f_t$ and

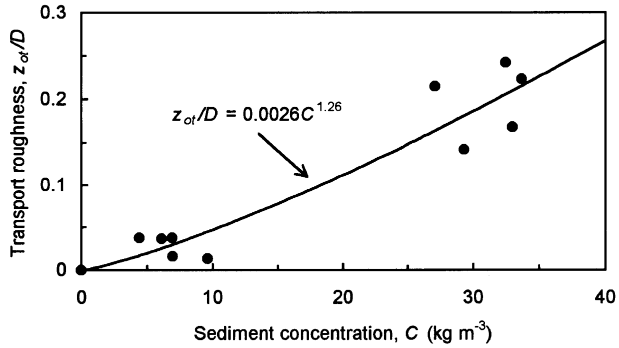

Figure 6. Graph of transport roughness against sediment concentration

$\%z_{ot}$ which assume that flow depth remains constant as sediment concentration increases. Table I confirms that in the present experiments this assumption is not far from the truth. The assumption can be justified on the grounds that although flow depth increases with sediment concentration, the increase is so small that it has a negligible effect on $\%f_t$ and $\%z_{ot}$.

The expressions for $\%f_t$ and $\%z_{ot}$ are:

$$\%f_t = 100[1-(U_s^2/U_c^2)] \tag{10}$$

and

$$\%z_{ot} = 100\{1-[\exp(U_s/m_s - U_c/m_c)]\} \tag{11}$$

where U_s is the mean velocity of a sediment-laden flow whose velocity profile has a slope of m_s and U_c is the mean velocity of a sediment-free flow whose velocity profile has a slope of m_c. Equations 10 and 11 show that both $\%f_t$ and $\%z_{ot}$ increase as the difference between U_c and U_s increases. But, $\%z_{ot}$ also increases as the difference between m_s and m_c increases and the absolute values of m_s and m_c decrease. Thus, the tendency for $\%z_{ot}$ to increase more rapidly than $\%f_t$ with $\%q_s$ is evidently due to the added effect of m_s and m_c on $\%z_{ot}$.

CONCLUSION

This study has evaluated the effect of saltating sediment on flow resistance and bed roughness in overland flow on a fixed sand-covered bed. The experiments were conducted on a relatively gentle slope of 2·7°, with Reynolds numbers less than 14 000 and sediment loads up to 87·0 per cent of capacity. Under these conditions, saltating sediment accounted for as much as 20·8 per cent of flow resistance and 89 per cent of bed roughness. Where slopes are steeper and sediment is finer, the same discharge will be capable of transporting a much larger sediment load in saltation, and commensurate increases in flow resistance and bed roughness are to be expected.

Thus it appears that saltating sediment has a considerable impact on overland flow hydraulics, at least on fixed granular beds. However, most hillslopes, whether natural of disturbed by agriculture, are hydraulically very rough, and resistance to flow is dominated by form and wave resistance (Abrahams *et al*., 1992; Abrahams and Parsons, 1994). Consequently, saltating sediment is likely to be less important on such hillslopes than it is in the present experiments. Still, saltation is generally of greater significance in overland flow than in river flow, and for this reason its effect on overland flow hydraulics is deserving of further study.

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